Application of the hammering test and acoustic emission technique to stone cultural properties

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Introduction

Most stone cultural properties are exposed to open air. They are weathered by various environmental factors, including physical, chemical and biological factors as well as combinations of these. To conserve a stone cultural property, it is important to survey the deterioration and its causes, and then to discuss the method of conservation. Firstly, it is necessary to discuss the possibility of removing the deterioration factors. Water is often a factor in stone weathering. To remove the influence of rainfall, the stone object can be covered by a roof. Various conservation treatments, such as reinforcement and water repellent, are often applied. After the environmental improvement and conservation treatment, it is important to monitor the environment and degradation condition of the stone. When problems are found, countermeasures have to be considered.

There are many non-destructive methods to detect the deterioration of stone cultural properties. Absorbance of infrared light is measured to estimate the moisture ratio of the stone surface. Thermography is used for visualizing the temperature distribution on the surface. For the mechanical strength of the stone, measurement of the velocity of an elastic wave, a Schmidt hammering test and a needle penetrating test are performed. The acoustic emission test is one of the methods of detecting minute destruction in stone. The application of the hammering test and the acoustic emission (AE) technique to estimate the deterioration and its causes will be introduced in this paper.

Fig. 1 Sonogram of hammering test

Fig. 2 Sonograms obtained from hammering test performed on concrete staircases. Left: sound part, Right: part with exfoliation

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Detecting exfoliation using the hammering test

Sound consists of three factors. They are frequency, amplitude and time duration. The hammering test is often applied to detect the exfoliation of concrete structures such as tunnels, walls of buildings and so on. This test can identify an inner defect in stone from an analysis of the sound that is made by hitting the stone surface with a hammer.

A sonogram is obtained from an analysis of the sound of hammering the stone. Fig.1 shows a model of such a sonogram. In this diagram, the horizontal and vertical axes respectively show the duration and frequency of the sound. In the case of a non-deteriorated stone, a short sound with a higher frequency is measured (A zone). In the case of a deteriorated stone, a lower frequency with a longer duration is observed, and consequently the shape of the sonogram is a triangle distribution (B zone). If the stone has exfoliation, the duration of certain frequencies is longer (C zone).

For example, two sonograms obtained in an experiment performed on concrete staircases are shown in Fig.2. A sonogram of a part of the concrete without exfoliation shows a short duration and higher frequency. This type of A zone sonogram shows that the strength is high. On the other hand, a sonogram of a part with exfoliation shows a long duration at 1.5 kHz. This is a so-called C zone. This C zone represents the existence of exfoliation. The lower frequency components corresponding to a B zone signify that the strength of this area is lower. Thus, the existence of exfoliation can be detected and strength can be estimated using the hammering test.

Two examples of hammering tests for stone cultural properties will be introduced. One was performed on base stone (Fig.3) excavated from the archaeological site of the Rasho-mon gate, which was the main gate of the Heijyo-kyo capital in the eighth century, Nara city, and for the other was performed on the chamber stone of Takamatsuzuka tumulus. The former is welded tuff, and latter tuff breccia.

Before the results of the hammering test for the base stone of the Rasho-mon were determined, thermography and measurement using a concrete tester were applied. Fig.4 is a subtraction image between thermograms at p.m. 01:09 and at p.m. 04:39. It is seen from this subtraction image that extreme temperature changes occurred in some parts. As a result, it can be only determined by thermography that there are abnormal parts.
A concrete tester is used to measure the mechanical strength of concrete. The result of the concrete tester measurement is shown in Fig.5. Comparing this result with the thermal subtraction image, it can be seen that the area shown in warm colors in the thermal subtraction image has lower strength and that shown in cold colors has higher strength.

Figure 6 shows sonograms from the hammering test for the base stone of Rasho-mon. Each sonogram was obtained from different parts which showed difference in thermal subtraction image. The areas shown in warm colors, which represent a large difference of temperature in the thermal subtraction image, exhibit a frequency band with a long duration time on the sonogram, so-called C zones. It is possible to speculate on the existence of exfoliation. On the other hand, the area shown in cold colors, which
represent a small difference of temperature in the thermal subtraction image, has a higher frequency component from 14 to 18 kHz with a short duration time. This finding suggested that this area has very high strength. These results are consistent with the results of the concrete hammer test. In the measurement with a concrete tester, it could be determined which part was a lower strength area, but it was not known whether exfoliation existed or not. In thermography, as mentioned before, it can be only known that some parts are something different in thermal behavior. Both of thermography and measurement of with a concrete tester, however, are very useful methods in the field, so those methods and the hammering test can be combined to form a very effective method.

Takamatsuzuka tumulus was excavated in 1972. It is believed that it was built between the end of the seventh century and the beginning of the eighth century. The stone chamber was built with tuff breccia. In the stone chamber, murals were painted on the ceiling and walls. The discovery of this tumulus with such colorful mural paintings was indeed the first such find in Japan, and it triggered an archeological boom in Japan, which contributed greatly to the development of archaeology. In 1973, the Tumulus was designated as a historic site, and in 1974 the murals were designated as a national treasure. However, the murals were damaged by biodegradation. In 2006, the Agency for Cultural Affairs of Japan decided that the stone chamber was to be dismantled, removed, and relocated to appropriate conservation facilities.

In this excavation research, there are variable findings regarding the construction method of this Tumulus during the last phase of the so-called age of...
Knowledge about the causes of the deterioration of the murals was also obtained. At the same time, the shape of the stones in the stone chamber was very different from the general expectation. The stones had many cracks that could not be detected from inside the chamber. In the dismantling of the stone chamber, specially developed jigs were used with special attention. All of the chamber stones were removed and transported to the conservation facilities without any damage, and have been kept in a very stable environment.

The chamber stones had very complex cracks, and sometimes contained exfoliations which could not be detected from the surface. Before each chamber stone was removed, the hammering test was carried out to detect the exfoliation of the stone surface, as it was necessary to accurately determine where the cracks existed, which parts had exfoliation, and how strong those parts were. Fig.9 shows the result of the test for points A and B in Fig.8. At point A, the duration time was long and a lower frequency was detected. This suggests that this area had exfoliation and lower strength. At point B, the area was found not to have deteriorated.

Monitoring of the dismantling of the chamber stones from Takamatsuzuka tumulus using AE Technique

When certain force is applied to an object as potential energy, the object is moved, deformed or destroyed to emit the energy, thus creating a new broken-out section, performing the work of movement, or producing thermal energy. At the same time, when the object gets deformed or fractured, sound is generated as one energy form. This phenomenon is called acoustic emission (AE).

The AE technique was applied to the dismantling of the stone chamber of Takamatsuzuka tumulus. The chamber stones of Takamatsuzuka tumulus were tuff breccia, as mentioned above. These chamber stones had some severely weathered parts. No more than the necessary force was applied in order to avoid causing the cracks to progress.

Figure 11 shows plots of AE count numbers versus time with a change of stress on a jig used to hold a chamber stone. The AE detected between 11:16:24 and 11:19:14 was caused by contact with metal tools, not by the destruction of stone. AE was detected when separating a stone from another stone.
The AE between 11:35:34 and 11:36:15 accompanied a change of stress to the jig and is not considered noise. During the lifting and horizontal moving of a stone, AE occurred, accompanied by a stress change of the jig. As these instances of AE were not continuous and did not increase, it seems that progressive destruction of stone did not occur. It is thought that these instances of AE were caused by a mechanical problem with the cranes.

**AE detection in stone during the temperature changing process**

Figure 12 shows the Western Top ruin, which lies to the west of Bayon in Angkor Thom, Cambodia. The structure was built using sandstone in later ages to cover the existing stupa built with laterite block. However, the laterite block used to build the existing stupa is extremely weathered and nearly collapsed, and some parts have now reverted to earth. Thus, the sandstone structure has become very unstable, and the structure itself is almost falling down.

Stone expands with increases in temperature. If a stone with a crack is partially heated, the crack will extend. From a detailed observation of the sandstones of Western Top, it is seen that they have many cracks.

![Western Top ruin in Angkor Thom, Cambodia](image1)

**Fig.12 Western Top ruin in Angkor Thom, Cambodia**

![Measurement of AE and temperature at Western Top ruin](image2)

**Fig.13 Measurement of AE and temperature at Western Top ruin**

![AE counts and temperature change of sandstone in the course of a day](image3)

**Fig.14 AE counts and temperature change of sandstone in the course of a day**
along with the stratification planes and exfoliations of the surface. Some portions, i.e., the upper part of the stone, are constantly exposed to sunlight during the daytime. Others, the lower and inner sides, receive very little sunlight. Thus, the temperature distribution in the stone is uneven.

The four temperature sensors were attached to the stone using gummed tape. Each AE sensor was attached near each temperature sensor. Fig. 7 shows the temperature changes (lines) and AE count numbers (points) at four points. At the beginning of the measurement, the surface temperatures of these points were 29 °C uniformly. At 1:00 p.m., the difference in temperature reached 12.5 °C. AEs were detected remarkably between 11:00 a.m. when the difference in temperature first appeared and 1:00 p.m. when the difference reached its maximum. After that, AE counts decreased gradually. The count numbers of an AE sensor that was placed near the crack increased especially. This result suggests that minute destruction and deformation may be caused at this point.